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PAPERS ON SLEET AND GLAZE ("ICE STORMS").

The freezing of rain onto wires, trees, and streets is so disastrous to telephone, telegraph, and power lines and radio-station aerials, to trees, and to transportation facilities that such means as can be employed to combat the formation of ice should be made ready before an "ice storm" begins. This involves forecasting the conditions which will cause the glaze to form, i. e., conditions such that liquid drops of water will fall from a relatively warm wind into cold air near the ground. The occurrence of sleet as well as the formation of glaze usually marks such a condition of the atmosphere and thus is a valuable (and noisy) index to glaze formation.

While the form of the precipitation reaching the earth's surface allows a fairly accurate surmise to be made as to critical temperatures aloft, actual observations by means of kites or airplanes, taken in conjunction with observations made at the surface, offer the best basis for "ice-storm" forecasts.

The first article indicates the general conditions under which sleet (and glaze) is formed, and the second discusses the actual meteorological features accompanying the storm of January 20 to 25, 1920, long to be remembered for the great destruction and inconvenience caused by the thick ice which formed over hundreds of thousands of square miles in the eastern United States.—EDITOR.

THE NATURE OF SLEET AND HOW IT IS FORMED.

By CHARLES F. BROOKS, Meteorologist.

[Weather Bureau, Washington, D. C., Apr. 5, 1920.]

SYNOPSIS.

Whereas in current practice in the United States, *sleet* is that form of precipitation which is not snow, rain, or hail, an attempt to make a detailed descriptive and genetic definition seems advisable, and 30 cases of sleet are analyzed as a basis:

Sleet, a rattling type of ice precipitation formed in the free air, has the following characteristics: *Size*, smallest dimensions of largest pieces less than 6 mm. (¼ inch); *form*, angular, irregular, or nearly spherical; *structure*, nongranular ice, part or all of which is cloudy or bubbly (except in extremely small drops), not more than one clear layer.

A sleet particle may be (1) a snowflake partly melted and refrozen, (2) a frozen raindrop, or (3) a frozen combination of snowflake, and raindrop or liquid (not undercooled) cloud droplets.

A generalized vertical section of sleet weather shows sleet as occurring usually with a cloud from which snow is falling through a stratum of air having a temperature above freezing and into air with a temperature below freezing.

INTRODUCTION.

Snow, sleet, rain, and hail are the names applied in the United States to all kinds of precipitation falling to earth out of the free air. Rain and snow need no definition here, and hail, with its large size, usual concentric layer structure, and association with strong thunderstorms, is definitely pictured in the minds of most observers. Thus, sleet, more or less by elimination, covers the great variety of ice particles which seem to give us frozen pictures of every step in the melting transition from snowflake to raindrop. In what category should "graupel" those granular white pellets, like compact miniature snowballs be placed—snow, sleet, or hail? Various names have been applied abroad, e. g., *snow pellets, soft hail, winter hail, grésil, Graupeln* (1).

SLEET DEFINITIONS.

It is no wonder then that there has been some difficulty in defining *sleet*. This will be obvious from a glance at Dr. Cleveland Abbe, jr.'s article, "American Definition of 'Sleet.'" (2) So far as the application of the word *sleet* to a form of precipitation generated in the atmosphere is concerned, there are the following outstanding features evident in this discussion: That "*nothing is sleet that does not rattle on a tin roof or against a window pane,*" (C. Alphonso Smith), and that *all sleet is either frozen rain drops or a mixture of rain and snow.* But how can a mixture of rain and snow rattle? Only by being a refrozen or partly refrozen mixture of the two. In the British Isles *sleet* is defined as, "Precipitation of rain or snow together or of partially melted snow." (7) The Weather Bureau's sleet committee, in consequence of not being able to make compatible the definitions mentioning a mixture of rain and snow on the one hand, and frozen raindrops on the other hand, omitted the former conception entirely and the then current (since about 1897) Weather Bureau instructions were continued:

> Care should be taken in determining the character of precipitation when in the form of sleet or hail. Only the precipitation that occurs in the form of frozen or partly frozen rain should be called *sleet*. Hail is formed by accretions consisting of concentric layers of ice, or of alternate layers of ice and snow. It frequently happens that snow falls in the form of small round pellets, which are opaque, having the same appearance as snow when packed. This should never be recorded as sleet.—*Weather Bureau* "Instructions for preparing meteorological forms," Washington, 1913, paragraph 119.

The Weather Bureau thus defined *sleet* as a frozen, hard, practically spherical form of precipitation, and differentiated between *sleet* and *snow* on the basis of whether or not the form of precipitation looks like a frozen or partly frozen raindrop. The distinction is a hard one to draw in practice, for there is no break in the gradation between snow and rain, or therefore, in the gradation of the frozen counterparts of this transition. There was no place in the Weather Bureau definition for irregular pieces of ice. These considerations led to the omission of all but the first sentence in the paragraph 119 quoted, as published in the revised instructions, which went into effect January 1, 1920. Uniformity in practice in recording sleet, however, demands a definition. This can be purely descriptive, or, better still, in part genetic so that the two elements of the definition will reinforce each other and leave no doubt as to what is meant.

Etymologically, *sleet* rattles on striking a hard object, and, therefore, it includes those irregular, partly melted, refrozen snowflake remnants, as well as the small, nearly spherical "frozen raindrops." It is much easier to differentiate a form of precipitation that rattles from one that does not than to draw the line between one that looks like a frozen raindrop and one that does not. A man who has to face a sleet storm places in the same category all forms that sting.

OBSERVATIONS OF SLEET PARTICLES.

The discussion of sleet definition and mode of formation aroused at the Second Pan American Scientific Congress, December 30, 1915, by Dr. Frankenfield's paper, "Sleet and ice storms in the United States," (3) made it obvious that statistical evidence as to the actual nature of sleet particles was necessary. So, 22 of the subsequent occurrences of sleet which I observed at New Haven, Conn., in 1916, 1917, and 1918 were carefully noted.

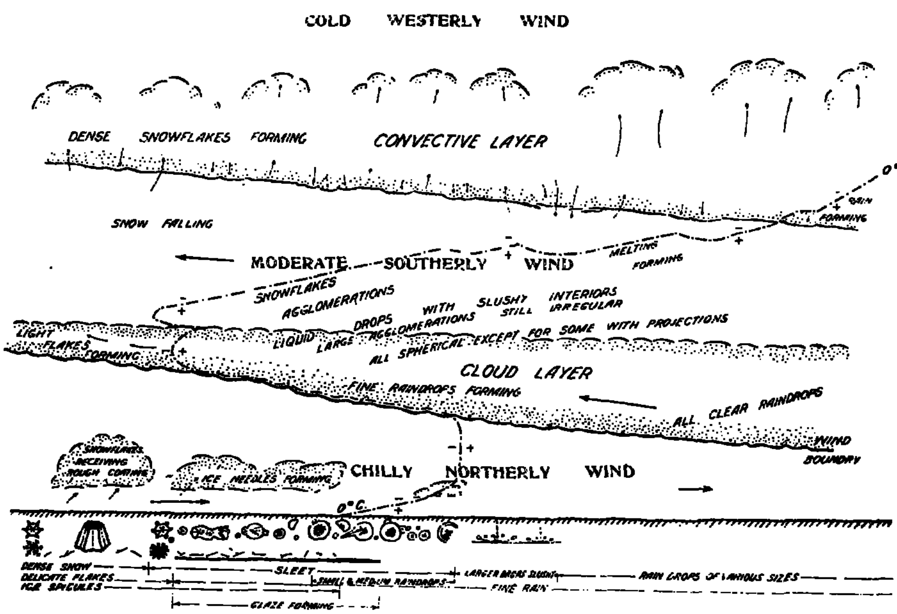

FIG. 1.—Composite diagram showing north-south section of the lowest 3 or 4 kilometers of the atmosphere probably responsible, at least on some occasions, for the formation of the various types of snow, sleet, and rain and the formation of glaze as shown at bottom. (If freezing temperatures near the surface extended beyond the right of the diagram some of the sleet would never have started as snow).

form about 0.5 mm. thick and 2 mm. in diameter. Most of the falling sleet particles were ¾ to 1 mm. in diameter, and some of the irregular pieces were 2 mm. long. Except for distortions the form of most approached the spherical. All particles were slightly cloudy inside except some of the smallest, which looked like clear ice. This sleet was evidently formed by the melting and refreezing of separate snowflakes, and particles were small because the snow crystals, being dense, did not become massed into large flakes while passing through the warm current.

Precipitation ceased from about 7:40 to 8:10 a. m. Then fine, liquid drops of rain, and some sleet fell for 15 minutes. Some glaze formed, as the temperature of the lower air was about −2° C. From 8:30 to 9:05 a. m. larger sleet fell. It was of irregular, half-melted, refrozen flakes, which looked white while falling through the air. Accompanying this sleet fall there were two types of snowflakes—one kind thin and light (a perfectly symmetrical 12-pointed one was seen) and the other kind thick, almost like a pellet. More glaze formed at about 9:15 and some sleet like that of the early morning fell again. Snow without accompanying sleet continued for the rest of the day from shortly after 10 a. m. with a northeasterly wind and falling temperature. The compact snowflakes seem to have come from a layer of cloud above a relatively warm, probably southerly, wind which must have been flowing over the cold surface wind. The intermissions in the precipitation may have been due to breaks in this upper cloud, and the final cessation of sleet due to the fall of temperature of the southerly wind to below 0° C. The fine raindrops, thin snowflakes, and the large, white sleet seem to have fallen from a low cloud the vertical extent of which reached from the lower cold current and through the warm one to a height exceeding the level where a temperature below 0° C. again occurred. From the base of such a cloud the thin snowflakes could fall without melting, in

Observations of 8 other cases in 1912, 1914, 1919, and 1920 bring the total up to 30. The dates were as follows:

1912: February 26 (Cambridge, Mass.).
1914: January 31 (Cambridge, Mass.).
1916: January 12, 20, 30; February 2, 12, 13, 18; March 6, 8, 14, 15; April 8 (New Haven, Conn.).
1917: January 31; February 5, 19; March 17; April 5, 26 (New Haven, Conn.).
1918: February 6, 9; April 10, 11 (New Haven, Conn.).
1919: March 15; December 14 (Washington, D. C.).
1920: January 22; February 4, 5, 14 (Washington, D. C.).

The details of some of the occurrences are, perhaps, worth publishing. The following are arranged roughly to show the transition in form between the but slightly melted refrozen snowflakes to what may have been actual frozen raindrops:

February 2, 1916.—The sound of falling, hard ice particles began before dawn. At 7:15 the ground was white with a covering half snow and half sleet. The snow was in single crystals generally of compact

the middle the liquid raindrops could be formed, and light snowflakes forming in the top and aggregating on falling through the warm layer would refreeze on passing through the cold air near the surface.

The warm wind aloft seems to have strengthened during the afternoon, and its under boundary must have been low, for from 4 to 9:10 p. m. barometric ripples of about 0.05 inch amplitude in intervals of a few minutes were traced by the barograph, and the pressure was falling. Some sleet occurred at 8:40 p. m. and the snowflakes later were hard and thick. The evening temperature was about −5° C.

February 18, 1916.—Melting sleet fell with a brisk rain between 4:10 and 4:25 p. m. The surface wind was about south, and the temperature 1° C. At 4:30 p. m. the sun shone and the wind changed to westerly. The sleet was obviously the partly refrozen remnants of half-melted snowflake agglomerations. They ranged from irregular white pieces about 2 mm. in diameter to hard, clear-surfaced ones about 1 to 2 mm. in diameter. The white ones became transparent very quickly on melting. Sleet is commonly formed from melting snow falling as in this case through a wedge of cold air which arrives at a moderate elevation just before the surface wind shifts on the passage of a low-pressure trough.

January 30, 1916.—A light fall of sleet occurred from 7:30 to 7:40 a. m. The pellets were generally oblate spheroids of 1.5 to 4 mm. diameter, the majority being 3.5 to 4 mm. Adhering, minute drops of ice (one of less than 0.5 mm. diameter was seen) and protruding thin plates and arms of unmelted snowflakes brought the length of some up to 7 mm. Most had snowy interiors, but were largely of clear ice. Many (from the impact of their fall, perhaps) became hollow, as if the drop had frozen only to a depth of 1 to 1.5 mm., and then the water had run out. A misting rain began coincidently with the sleet-fall, and glaze formed till about 11 a. m., when the temperature rose to above freezing. The morning temperature was −1° C., and the wind light east. The large size of the sleet seems to have been due to the partial melting and refreezing of considerable agglomerations of flakes, a conclusion which is borne out by the occurrence of remnants of more than one flake in a single sleet particle. The minute drops were probably from the melting of individual crystals or from intercepted drops formed otherwise.

March 14, 1916.—A little rain began falling at 4:20 p. m. and sleet at about 7:30 p. m. Each particle was a thick and hard snowflake which had evidently been partially melted and refrozen in the lower air. The six points of the flakes were in many cases reduced to ice beads, while the inside parts still showed the delicate structure of a snowflake.

March 15, 1916.—During the night the northeast wind increased to strong and the temperature fell to −5° C. at 7 a. m. and to −7° C. at noon. All morning fine drops of liquid rain and small grains of snow 0.2 to 0.3 mm. in diameter were falling. At 1:10 p. m. the sky became very dark and at 1:20 large sleet began to fall (the small grains continuing), in a heavy shower at first. This sleet was 1.5 to 5 mm. in diameter, almost spherical, whitish and bumpy on the surface (probably from falling through a cloud of undercooled droplets), but with an outer layer of clear ice immediately below the surface and an inner core of cloudy ice. There were all sizes from 5 mm. down perhaps to 0.1 mm. between 1:30 and 2 p. m. Then snowflakes were first seen, and by 2:10 all the precipitation was in the form of snow. Many of the snow crystals were hard and fat, and there were several large, softer flakes.

February 4, 1920.[1]—After some heavy rain on the preceding evening, light rain and light sleet began at about 8 a. m., the sleet being nearly spherical (there were some hemispheres), 0.2 to 2 mm. in diameter, and all particles having cloudy centers. The light rain continued throughout the day, the sleet became heavy by late morning, and during two hours in midafternoon was mixed with snow needles (probably from the low clouds). The wind was brisk NE. and the low nimbus clouds, when visible, moved in turbulent manner from the ENE. At 5:45 p. m., among the large quantities of sleet falling, one pellet with an arm of a snow crystal projecting about 2 mm. beyond the surface, making the particle about 4 mm. long, was observed. The depth of sleet fall to 6:15 p. m. was 5 cm. The heavy sleet and light rain continued till about 8:30 p. m., after which the light rain and possibly some fine needles of snow fell during the night.

February 5, 1920.—In the morning low scud was moving from the northeast and small raindrops, scattered snow needles, and very small sleet, for the most part about 0.2 to 0.6 mm. in diameter, fell in small quantity. The wind was north-northeast to north. Snow needles were again seen at 2 p. m. Larger sleet, of ordinary character, fell in the late afternoon and in a shower during the evening. Light rain continued throughout. The clouds during the late afternoon were much less dense than on the preceding afternoon, for the daylight lingered noticeably longer.

January 31, 1914.—For a few minutes during the formation of glaze some sleet fell. "The individual pieces were generally spherical, but many were angular; some were flat on one side [split pellets], and others were agglomerations. The frozen drops varied between 0.5 mm. and 4 mm. in diameter. One pellet 3 mm. in diameter had two pellets 1½ and 1¼ mm. in diameter stuck to it, and one of ¾ mm. stuck to the 1½ mm. one. (See fig. 1). The structure of the sleet showed plainly [that] * * * snowflakes had passed into an air stratum whose temperature was above 0° C.; and [that] some, on reaching the colder layer below before entirely melting, froze. This is shown by the presence of snowflake skeletons, by angularity, and by the almost universal prevalence of minute bubbles in the ice. The unfrozen rain which reached the ground was rain formed within the warmer stratum and of entirely melted snowflakes. The short duration of the sleet may be explained by assuming that before and after its occurrence the warmer layer was so thick that none of the snow passed out of it partially melted." (4)

SUMMARY OF THE 30 OBSERVATIONS OF THE CHARACTER OF SLEET.

Size.—Most frequent, 2 to 3 mm. diameter. Extremes measured, 0.2 to 5 mm. diameter; irregular pieces, maximum length more than 10 mm.

Form.—Spherical, or nearly so, and not accompanied by irregular or angular pieces, 6 cases. Irregular or angular pieces, 20 cases. (Details not recorded in 4 cases.)

Structure.—Cloudy or bubbly cores—noted in all sleet, except for some of the very smallest drops. Ice shell, wet interior, 2 cases. Snow crystals or remnants visible, 10 cases.

Attendant rain or snow.—Liquid rain coincident with sleet fall, 22 out of 26 cases in which precipitation was noted. Sleetfalls immediately preceded, accompanied, or followed by snowfall, 15 noted.

A NEW DESCRIPTIVE DEFINITION OF SLEET.

These sleet observations are, perhaps, sufficient to validate the following descriptive definition:

Sleet, a rattling type of ice precipitation formed in the free air, has the following characteristics: *Size*, smallest dimensions of the largest pieces less than 6 mm. (¼ inch); *form*, angular, irregular, or nearly spherical; *structure*, non-granular ice, part or all of which is cloudy or bubbly (except in extremely small drops), not more than one clear layer.

This definition differentiates sleet from rain, since sleet is of ice particles; it differentiates sleet from snow, since sleet rattles and, unlike graupel which also rattles, bears evidence of having been in at least a partly liquid state, and it differentiates sleet from hail, since hailfalls in which the largest pieces are less than 6 mm. (¼ inch) through, are rare.

HOW SLEET IS FORMED.

What can observations of the nature of sleet tell as to its genesis?

Snowflake origin.—In practically all sleetfalls there is unmistakable evidence of snowflake origin; particles show snow crystal remnants, angularity, or included bubbles. Furthermore, the association of sleetfalls with coincident, immediately preceding, or immediately following snowfalls points in the same direction. In only 4 of the 30 sleet occurrences cited are indications of snow association lacking; and in these 4 the sleet pellets had cloudy cores, which may have been the last, unmelted remnants of snowflakes. Thus, we may say with confidence that few sleetfalls occur in which at least some of the sleet particles are not partly melted, refrozen snowflakes.

Frozen raindrops.—How common are frozen raindrops, i. e., sleet pellets formed from entirely liquid raindrops? A cake of artificial ice, frozen from the outside, has a cloudy core, so a frozen raindrop might reasonably be expected to have a cloudy core. There is nothing to indicate that frozen raindrops do not occur in some sleetfalls, either from the freezing of the raindrops from snowflakes entirely melted in passing through a warm stratum aloft, or from raindrops actually precipitated from the warm wind. The formation of raindrops from any but small snowflakes seems unlikely under sleet-forming conditions, as there is room aloft for but a relatively small thickness of air at temperatures above 0° C. Frozen raindrops will form from any drops cold enough,[2] which are of sufficient size to be rippled in falling through the air, and from any undercooled drops that collide. Several

[1] See also pp. 78 and 110 of this REVIEW.

[2] The following note may be illuminating on this point:

Super-cooled water.—With reference to this subject, which was mentioned in the last Circular (No. 23), Dr. John Aitken writes: "I was much surprised to read in your 'Official Notices,' No. 23, that the existence of pure water as a liquid at temperatures below the freezing point 'is naturally regarded as exceptional.' Now, this is far from the case. It is the rule water can no more begin to change to ice at its 'freezing point' than it can change to vapor at its 'boiling point,' or from vapor to water at its 'condensing point,' unless there is a 'free surface' present at which the change can take place. Water has always to be cooled some degrees below its 'freezing point' before ice begins to form, Nothing in nature with which water is in contact, such as particles of soil, stones, grass, etc., act as 'free surface,' though some of them seem to start the action with less subcooling than others. Yet all [?] require 1° or 2° C. subcooling before they start the change. The only substance known that will cause freezing to begin just below the 'freezing point' is a piece of ice or a snowflake. This slowness in starting the freezing and the time taken to freeze all the water on the bulb makes 'wet' and 'dry' readings of little value for temperatures about the 'freezing point.'"—*Meteorological Office Cicular* (London), No. 24, May 24, 1918, p. 2.

observed facts indicate that small, undercooled raindrops occur *not infrequently:* (1) Droplets that freeze onto objects without entirely flattening out; (2) the dryness of icy posts on which raindrops are continually falling; (3) the formation of glaze from raindrops on twigs and roofs where snowflakes had just been melting (5). Theoretical considerations of the rate of cooling of a raindrop and the known temperatures and thickness of below-freezing layers of air through which liquid raindrops fall confirm this (4) (6). The maximum size which such drops can attain without rippling on falling, is at least 0.5 mm. (measured on several occasions) and is probably 1 mm., and perhaps more in relatively calm air (in which the "air-speed" of the drop does not change as in passing through turbulent air).

The descriptive definition of sleet given on page 71 may be strengthened by the addition of the following sentence:

A sleet particle may be (1) a snowflake partly melted and refrozen, or (2) a frozen raindrop, or (3) a frozen combination of snowflake and raindrop or liquid (not undercooled) cloud droplets.

GRAUPEL.

Coated snowflakes.—A snowflake on falling through a cloud of undercooled liquid droplets is likely to become coated with a layer of rough ice if there is sufficient turbulence to make it fall with different sides downward. Such a coated snowflake becomes a pellet of the type usually known abroad as *soft hail, Graupeln,* etc. If, however, the falling crystal presents the same face downward throughout its passage through the wet cloud, the intercepted cloud particles may arrange themselves in accordance with the axes of the snow crystal. The following notes were written about such a case observed at New Haven, Conn., March 10, 1918, for a half hour at about noon; surface wind, west-north:

In the center of an intense cyclone, while the pressure oscillated slightly under the influence of the changing proportions of cool and warm air layers above, a fall of "soft hail" in the form of truncated fluted hexagonal pyramids, 3 to 5 mm. high and 3 to 5 mm. in diameter across the base, occurred. The tops of the pyramids were formed by symmetrical snow crystals and so were the bases. The sides were grooved corresponding to the indentations of the edges of the snow crystals. The texture was relatively coarse, and the structure partook of the character of mountain hoar frost [rime] which has formed in a windy fog, from the congealing of the cloud particles onto the already formed ice crystals.

Evidently there had been a fall of snowflakes from the upper nimbus, and these in passing through a quiet layer of stratus or fracto-nimbus had kept their horizontal positions and in this way accumulated more and more cloud droplets as they settled and grew in diameter. Mixed with the fall of "soft hail" were ice needles, representing, apparently, the direct condensation into ice which was taking place within the scud.

Genetically there is really but little difference between this collection of cloud particles on a falling snowflake and the collection of undercooled [?] raindrops on the falling hailstone. If the fracto-nimbus were turbulent the deposits might occur on all sides, making a rounded pellet.

Clouds at 8 a. m.: Layer at about 700 m. from west, Fr.Nb. below from northeast. Northwest wind-shift [followed with] snow squall [lasting till] 3 p. m.

A previously formed sleet particle may receive a rough coating by falling through a cloud of undercooled droplets.

SLEET, GRAUPEL AND HAIL CONTRASTED.

Sleet.—Partly melted snow or rain frozen while falling from a warm layer through a cold one. (Different from hail—not carried aloft by strong convection.)

Graupel.—Snowflake coated with rime on falling through a cloud of undercooled liquid droplets. (Different from sleet—temperature not above freezing aloft.)

Hail.—Accretion of snow and rain, usually in layers, formed by being carried by strong convection from a warm *up* to a cold level. (Different from sleet—no cold, surface layer necessary.)

VERTICAL SECTION OF SLEET WEATHER.

Figure 1 is a diagrammatic representation of the conditions which seem to be responsible for the formation of the various types of sleet observed. It is an improvement over its predecessor published in 1914 (4) in that it is more detailed and based on more observations. Still it is hypothetical in part, and it may be corrected by simultaneous observations at different levels on high towers and mountains or by means of kites, balloons, or airplanes.

CONCLUSION.

Close observation of the form of precipitation, of surface wind, temperature and pressure conditions, and of clouds, when interpreted in the light of some understanding of the processes of the atmosphere enable meteorologists to surmise with reasonable assurance what the winds and temperatures are aloft. Let us have *sleet* in our records always be significant of the probable occurrence of winds with above-freezing temperatures over a cold, surface layer of air.

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A WEATHER CONDITION WHICH PRODUCES GLAZE IN NORTHERN NEW YORK.

By DOUGLAS F. MANNING.
[Alexandria Bay, N. Y., Mar. 4, 1920.]

An interesting state of weather occurs here not infrequently during January, February, and March. Such a condition prevailed during March 2 and 3, 1920, proving that the intensely cold northerly winds sometimes extend only a short distance above the earth's surface.

Under such conditions, there is a fresh to brisk northerly to northeasterly wind of a temperature between 10° below zero F. and zero, or a few degrees above, and a sky covered with a warm-looking, smoky-appearing strato-cumulus cloud at moderate altitude moving slowly from the southwest or west and with which the sun, when seen shining through the occasional clear space, is a ball of lurid red.

Sometimes large feathery flakes of snow fall, the fact of the large flakes proving a warmer current aloft, and at